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Mixing due to a heated elliptic air jet

Zhenkuan Kenny Zhang, Leok Poh Chua [*]

School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore 639798, Republic of Singapore

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ABSTRACT

This paper presents measurements of velocity and temperature for a contoured contraction nozzle elliptic air jet with a 2:1 aspect ratio issuing into stagnant unconfined surroundings. Initial conditions at the jet nozzle exit plane were laminar. All measurements of mean and root-mean-square (RMS) velocities and temperatures were carried out using hot-wire and cold-wire anemometers. Flow development was found to be more rapid in the minor axis than major axis due to the thinner initial boundary layer momentum thickness in the minor axis plane. This is clearly demonstrated by the rapid growth of the jet width in the minor axis (compared to the major axis) in the near-field of the jet. Self-similarity in the mean velocity and temperature profiles was attained relatively early. However, RMS quantities have not become self-similar even by the streamwise distance of 38 equivalent jet nozzle diameters (D_e). One axis-switchover due to the initial difference in jet-width growth rates in the two axes was detected in the current jet. The rates of centerline temperature decay, temperature half-width growths and peak RMS temperatures at all measurement locations were consistently higher than their velocity counterparts. The temperature spreading rate in the major axis was found to be significantly larger vis-à-vis that of velocity, possibly due to the minima in radius of curvature of the elliptic geometry. All the results presented suggest that the use of heated elliptic jets could offer enhanced mixing performance in relevant applications.

1. Introduction

A jet issuing into a still environment or otherwise is a common type of free turbulent flow configuration. Characterized by high levels of turbulence intensity that accompanies downstream development as well as enhanced heat and momentum transfer by large-scale structures [1], jet applications are far-reaching, including but not limited to: the control of chemical reaction rates [2], and even the study of pollutant dispersion in the atmosphere which may be modeled after the spread of a turbulent jet [3].

Noncircular jets have received much attention as they pose as an attractive means of passive flow control at a relatively low cost of altering the jet nozzle geometry. Noteworthy performance gains include inter alia enhanced entrainment and subsequent mixing of the ambient fluid with the jet fluid—useful in chemical reactor applications, reduction of combustion instabilities leading to lowered levels of undesired emissions in combustors, turbulent noise suppression and thrust vector control [4,5].

The elliptic jet is a special member of the family of noncircular jets because unlike square or rectangular jets, it has no sharp corners, and serves as the intermediate between the two limiting extremes of possible jet shapes: the circular and planar jets. Elliptic jets are also classified as three-dimensional jets, exhibiting unique development in both major and minor axes planes in addition to downstream development, as compared to circular and planar jets. Focusing our literature survey and current experimental investigation to submerged (i.e., air jet in air) flows, elliptic vortex rings have been studied experimentally by Viets and Sforza [6] and have been found to be inherently unstable—the presence of lift and drag forces according to the analyses of Rankine vortices cause the elliptic ring to distort, unlike a circular ring which retains its shape in plane. Additionally, the local velocity of a curved segment of a vortex filament is found to be proportional to its radius of curvature due to the effects of self-induction [7]. Extending this analysis to elliptic jets, the distinguishing feature of variation in the azimuthal curvature stems from the non-constant radius of curvature of the ellipse, which imparts an initial boundary layer momentum thickness that varies continuously along the jet nozzle exit. This causes non-uniform self-induction of vortices resulting in complex three-dimensional deformation [8]. As a consequence, after some downstream distance the two span wise axes will interchange, appearing as if the jet column has rotated by 90°. Previously incorrectly thought to be due to a helical rotating action in which the jet column spirals with downstream development, studies have established that axis-switching is caused by unequal growth or spreading rates in the different axes of noncircular jets [5,9–11]. This

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[*] Corresponding author. Address: Nanyang Technological University, Division of Thermal and Fluids Engineering, 50, Nanyang Avenue, North Spine (N3) Level 2, Singapore 639798, Republic of Singapore. Tel.: +65 6790 5611; fax: +65 6792 4062.

E-mail addresses: zhan0293@e.ntu.edu.sg (Z.K. Zhang), mlpchua@ntu.edu.sg (L.P. Chua).

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Nomenclature

A_1	jet velocity decay rate
A_2	jet temperature decay rate
A_3	jet velocity spreading rate
A_4	jet temperature spreading rate
B_1	jet velocity kinematic virtual origin
B_2	jet temperature virtual origin
B_3	jet velocity geometric virtual origin
B_4	jet temperature geometric virtual origin
d	diameter of wire sensor
D_e	equivalent diameter of jet nozzle exit (mm)
Gr_j	Grashof number at jet nozzle exit
J	momentum flux (kg m s^{-2})
l	active wire sensor length
L_y	jet velocity half-width in the major axis plane (mm)
L_z	jet velocity half-width in the minor axis plane (mm)
$L_{\theta y}$	jet temperature half-width in the major axis plane (mm)
$L_{\theta z}$	jet temperature half-width in the minor axis plane (mm)
Re, Re_j	Reynolds number, Reynolds number at jet nozzle exit
T_j	jet exit temperature (°C above the ambient)
T_m	jet mean temperature (°C above the ambient)
T_rms	root-mean-square (RMS) temperature (°C above the ambient)
u'	root-mean-square (RMS) velocity in the x-direction (m/s), Reynolds normal stress in the streamwise x-direction
U_c	local centerline mean velocity (m/s)
U_j	jet exit velocity (m/s)
U_m	mean streamwise velocity (m/s)
x, y, z	distances in Cartesian coordinate system (mm)
y'	offset inward distance from nozzle lip in the y-direction (mm)
y''	offset outward distance from nozzle lip in the y-direction (mm)
z'	offset inward distance from nozzle lip in the z-direction (mm)
z''	offset outward distance from nozzle lip in the z-direction (mm)
Greek symbols	
θ	boundary layer momentum thickness (mm)
ν	kinematic viscosity (m^2/s)
ρ	fluid density (kg/m^3)
Others	
$'$	single prime mark denotes root-mean-square (RMS)
$_c$	subscript lower-case c denotes jet axis centerline values

phenomenon of axis-switching is of interest because of its contribution to the enhanced mixing properties of such jets.

Many jet applications in industry involve fluid emitted from the jet at an elevated temperature over the ambient. This would mean that the jet fluid could have an appreciably lower density than the fluid in the surroundings it is ejected in to. Brown and Roshko [12] found that a plane mixing layer spread more rapidly when the fluid density on the high-speed side of the layer is reduced relative to that on the low-speed side. Russ and Strykowski [13] reported for a circular contraction nozzle jet that increased rates of jet spreading and axial velocity decay are effects of the reduction of jet fluid density with respect to the ambient, regardless of laminar or turbulent initial conditions. Additionally, Yu and Monkewitz [14] also observed increased rates of jet spreading and consequently improved mixing between the jet and ambient fluids in their study of a heated two-dimensional planar jet approximated by a rectangular nozzle with an aspect ratio of 20:1 as compared to the non-heated case. Undoubtedly, heated or low-density buoyant jets form an important aspect of jet research, featuring prominently in applications such as fuel and air mixing in combustion chambers and jet engines. While investigations documented in the literature seem to focus on the impingement of single [15,16] or arrays [17,18] of elliptic jets onto heated surfaces and the ensuing flow and heat transfer characteristics, measurements of a heated elliptic free jet are scarce.

Self-preservation in the context jet flows is of interest because once this asymptotic condition is achieved, further downstream development of the flow can be predicted since the measured profiles of various flow quantities can be brought to congruence when normalized against local velocity and length scales. A hierarchy of self-preservation was reported by Bevilaqua and Lykoudis [19] in that mean quantities will become self-similar first, followed by fluctuating components and then higher order moments with increasing streamwise development distances. George [20] expanded on this, proposing that partial or full self-preservation states exist, and their attainment is governed by the initial conditions of the flow.

Given the far-reaching applications of noncircular and heated jets, the aim of this paper is to present some velocity and temperature measurements for a heated elliptic jet with a 2:1 aspect ratio and laminar initial conditions issuing into free surroundings. The working fluid is ambient air, and the jet issues into nominally still, unconfined surroundings. The axis-switching observations, self-preservation in the near-field mixing layer as well as in the far-field are discussed.

2. Experimental arrangements

The experimental rig is shown schematically in Fig. 1 and the coordinate system is defined in Fig. 2. The origin for the Cartesian coordinate system adopted is at the center of the ellipse, at the nozzle exit plane. Additionally, y' (z') and y'' (z'') are offset coordinates measured inwards and outwards respectively from the elliptic nozzle lip along the major (minor) axes. A centrifugal blower driven by a variable speed, alternating current three-phase induction motor draws in ambient air in the laboratory and supplies the jet flow. Speed regulation of the motor is achieved by a frequency control system with a pulse width modulation inverter. Installed downstream of the blower are a divergence section and a settling chamber. Mesh screens and a honeycomb section were used to reduce the turbulence intensity and straighten the flow respectively. A transition piece after the settling chamber changes the square cross-sectional duct of the flow system (250 mm × 250 mm) to an ellipse with a 2:1 aspect ratio (250 mm × 125 mm). A smooth contoured duct with a 25:1 contraction ratio fabricated from fiberglass then produces the final 2:1 aspect ratio elliptic jet nozzle exit (50 mm × 25 mm). The overall length of the flow system measured from the centrifugal blower to the jet nozzle exit is approximately 1900 mm. The equivalent diameter, D_e, defined for the present jet as the diameter of a circular jet with the same exit momentum flux, is 35.4 mm.

For the heated jet measurements, a 1 kW electrical coil element heater attached to the inlet of the centrifugal blower is used. This